LETTER

Improvement of JPEG Compression Efficiency Using Information Hiding and Image Restoration

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SUMMARY The application of information hiding to image compression is investigated to improve compression efficiency for JPEG color images. In the proposed method, entropy-coded DCT coefficients of chrominance components are embedded into DCT coefficients of the luminance component. To recover an image in the face of the degradation caused by compression and embedding, an image restoration method is also applied. Experiments show that the use of both information hiding and image restoration is most effective to improve compression efficiency.
key words: *information hiding, image compression, image restoration, JPEG, color image*

1. Introduction

Information hiding includes watermarking and steganography [1], where some kind of useful information is embedded into media data such as digital still images or audio data. As a new application of information hiding, this paper investigates its application to image compression. Specifically, we aim to improve the compression efficiency of JPEG color images, i.e., to increase JPEG image quality at the same bit rate (file size) or equivalently to reduce bit rate at the same image quality. Note that we do not aim to improve it by tuning quantization tables used for JPEG compression of color images but aim to improve it under any quantization tables used.

In JPEG compression of color images, colors are represented by luminance and chrominance (YCbCr) components. Then considering characteristics of human vision system, chrominance (CbCr) components are represented more coarsely than luminance component. That is, Cb and Cr components are usually downsampled by a factor of two in the compression stage to improve compression efficiency. Then the discrete cosine transform (DCT) is applied to nonoverlapping 8×8 pixel blocks in each component image. Derived DCT coefficients are subjected to quantization, where DCT coefficients of chrominance components are generally quantized more coarsely than those of luminance component. After quantized DCT coefficients are encoded by entropy coding such as Huffman coding, JPEG compressed image data is finally derived.

To improve the compression efficiency of JPEG color images, we investigate the approach whereby entropy-coded chrominance components are embedded into quantized DCT coefficients of luminance component. Given an original color image, a JPEG compressed gray image with chrominance components embedded is derived which seemingly has only luminance component. Even if data size of chrominance components can be reduced by embedding, quantized DCT coefficients of luminance component are changed by embedding from those without embedding. This degrades image quality and can increase data size of luminance component. To improve compression efficiency, we need to use such an embedding method that changes the values of the DCT coefficients as little as possible, to be precise, minimizes distortion of DCT coefficient caused by quantization and embedding. An embedding method using quantization index modulation (QIM) [2] at quantization step of DCT coefficients [3] is here used as such a method*. Furthermore, an image restoration method based on maximum a posteriori (MAP) estimation [4] is also applied to recover the image degradation caused by compression and embedding.

As far as we know, there is only one paper [5] relevant to this study, where among quantized DCT coefficients, Huffman encoded DC (direct current) component is embedded into AC (alternating current) components. Since the resulting image by applying this method has only AC components, it does not comply with the JPEG image format and therefore it does not seem natural and innocent. We believe that applications of information hiding might need to meet such a requirement that resulting images seem natural and innocent. The resulting image by the proposed method is seemingly a natural JPEG gray image and it can be seen by using a usual JPEG decoder. Additionally, the proposed approach can be taken as a typical application of steganography that a JPEG gray image can be viewed by anyone but its color version can be viewed only by privileged persons.

2. Outline of Proposed Method

A flowchart of the proposed method is shown in Fig. 1, where Fig. 1 (a) and Fig. 1 (b) are those for encoding pro-

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*As is described in Sect. 3, QIM needs an original image as side information. Therefore the proposed method using QIM cannot be applied to already JPEG compressed images. If a better embedding method which does not need an original image is developed, it can be applied to JPEG images.

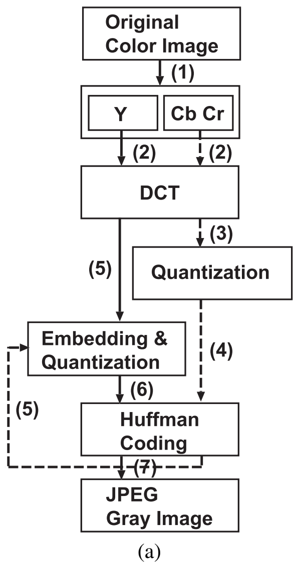

Fig. 1 A flowchart of the proposed method: (a) encoding process, (b) decoding process.

cess and decoding process, respectively. In the figures, each number means processing order and processes for Cb and Cr components are shown with dashed lines. In encoding process shown in Fig. 1 (a), colors in an original image are transformed to YCbCr components and DCT is applied to each component image. DCT coefficients of CbCr components, which are quantized and encoded by Huffman coding in advance, become data to be embedded into quantized DCT coefficients of Y component ((3), (4), (5) in Fig. 1 (a)). Data embedding is carried out at the quantization step for Y component using QIM. Quantized DCT coefficients of Y component image are encoded by Huffman coding, and finally a JPEG gray image is derived.

In decoding process shown in Fig. 1 (b), applying Huffman decoding to the JPEG gray image data, quantized DCT coefficients of Y component are derived. Embedded data that is Huffman encoded CbCr components is extracted from the quantized DCT coefficients of Y component. Then by applying Huffman decoding to the extracted data, quantized DCT coefficients of CbCr components are derived ((3), (4) in Fig. 1 (b)). To retrieve YCbCr components from those quantized DCT coefficients, the inverse DCT is applied to those quantized DCT coefficients. Finally, image restoration using the MAP estimation is applied to YCbCr components.

The two key techniques used in the proposed method, i.e., data embedding into DCT coefficients using QIM [3] and color image restoration using the MAP estimation [4] are briefly described in the following sections 3 and 4, respectively.

3. Data Embedding into DCT Coefficients Using QIM

Data embedding in DCT domain is usually carried out after quantization step by changing a value of quantized DCT coefficient according to a message to be embedded. Examples include J-Steg [6] and F5 [7]. However in embedding using QIM, it is carried out at the quantization step using a real-valued DCT coefficient.

Consider embedding a binary message $m \in \{0, 1\}$ to each DCT coefficient. Assuming that each real-valued DCT coefficient is divided by its quantization step size[†], we prepare two different quantizers to embed a binary data. One quantizer whose codebook consists of even numbers is used to embed 0 and therefore the closest even number to a real-valued DCT coefficient is set as its quantized DCT coefficient. Alternatively to embed 1, the other quantizer whose codebook consists of odd numbers is used and the closest odd number to the real-valued DCT coefficient is set as its quantized DCT coefficient. Mean square distortion caused by quantization and embedding using QIM is 4/7 of that using conventional embedding methods such as J-Steg and F5 [8]. Therefore, image quality after embedding by QIM is less degraded than that by other methods. However, note that QIM needs an original image because it needs real-valued DCT coefficients as side information while other methods do not need it.

4. Color Image Restoration Using MAP Estimation

Let $\mathbf{x}_{\mathcal{L}} = \{\mathbf{x}_{ij}; (i, j) \in \mathcal{L}\}$ and $\mathbf{z}_{\mathcal{L}} = \{\mathbf{z}_{ij}; (i, j) \in \mathcal{L}\}$[††] denote an original color image and its JPEG compressed one, respectively, defined on a two-dimensional lattice $\mathcal{L} = \{(i, j); 1 \leq i \leq N_1, 1 \leq j \leq N_2\}$. In YCbCr color space, $\mathbf{x}_{ij} = (y^X_{ij}, cb^X_{ij}, cr^X_{ij})^T$, i.e., a color vector at (i, j) pixel is composed of a luminance component y^X_{ij} and two chrominance components cb^X_{ij} and cr^X_{ij}. Given a compressed image $\mathbf{z}_{\mathcal{L}}$, its original image $\mathbf{x}_{\mathcal{L}}$ can be estimated by maximizing a posteriori probability $p(\mathbf{x}_{\mathcal{L}} \mid \mathbf{z}_{\mathcal{L}})$, i.e., by MAP estimation. The MAP estimate $\hat{\mathbf{x}}_{\mathcal{L}}$ is written as

$$\hat{\mathbf{x}}_{\mathcal{L}} = \arg\max_{\mathbf{x}_{\mathcal{L}}} p(\mathbf{x}_{\mathcal{L}} \mid \mathbf{z}_{\mathcal{L}}). \tag{1}$$

The MAP estimation problem for a whole image in (1) is approximately decomposed into local MAP estimation problem for each pixel.

$$\hat{\mathbf{x}}_{ij} = \arg\max_{\mathbf{x}_{ij}} p(\mathbf{x}_{ij} \mid \mathbf{z}_{ij}, \mathbf{x}_{\eta^X_{ij}}), \tag{2}$$

where pixelwise a posteriori probability is given by

$$p(\mathbf{x}_{ij} \mid \mathbf{z}_{ij}, \mathbf{x}_{\eta^X_{ij}}) = \frac{p(\mathbf{z}_{ij} \mid \mathbf{x}_{ij}) p(\mathbf{x}_{ij} \mid \mathbf{x}_{\eta^X_{ij}})}{\sum_{\mathbf{x}_{ij}} p(\mathbf{z}_{ij} \mid \mathbf{x}_{ij}) p(\mathbf{x}_{ij} \mid \mathbf{x}_{\eta^X_{ij}})}. \tag{3}$$

Here $\eta^X_{ij} \subset \mathcal{L}$ denotes the (i, j) pixel's neighborhood of a random field $x_{\mathcal{L}}$. For $p(\mathbf{z}_{ij} \mid \mathbf{x}_{ij})$, the following Gaussian probability density function (pdf) is assumed.

[†]Given quantization tables and quality factor value for JPEG compression, quantization step size for each frequency component is automatically determined.

[††]In this paper, x_A and $f(x_A)$ denote the set $\{x_{a_1}, \ldots, x_{a_l}\}$ and the multivariable function $f(x_{a_1}, \ldots, x_{a_l})$ respectively, where $A = \{a_1, \ldots, a_l\}$.

$$p(\mathbf{z}_{ij} \mid \mathbf{x}_{ij}) = \frac{1}{(2\pi)^{3/2}|\mathbf{\Sigma}_E|^{1/2}} \exp\{-\frac{1}{2}(\mathbf{z}_{ij} - \mathbf{x}_{ij})^T (\mathbf{\Sigma}_E)^{-1}(\mathbf{z}_{ij} - \mathbf{x}_{ij})\}, \quad (4)$$

where $\mathbf{\Sigma}_E$ is the covariance matrix of the error vector $\mathbf{e}_{ij}$ ($\mathbf{e}_{ij} = \mathbf{z}_{ij} - \mathbf{x}_{ij}$) introduced by lossy compression. For $p(\mathbf{x}_{ij} \mid \mathbf{x}_{\eta^X_{ij}})$, a Gaussian Markov random field characterized by the following local conditional pdf is used as a color image model.

$$p(\mathbf{x}_{ij} \mid \mathbf{x}_{\eta^X_{ij}}) = \frac{1}{(2\pi)^{3/2}|\mathbf{\Sigma}_X|^{1/2}} \exp\{-\frac{1}{2}(\mathbf{x}_{ij} - \bar{\mathbf{x}}_{\eta^X_{ij}})^T (\mathbf{\Sigma}_X)^{-1}(\mathbf{x}_{ij} - \bar{\mathbf{x}}_{\eta^X_{ij}})\}, \quad (5)$$

$$\bar{\mathbf{x}}_{\eta^X_{ij}} = \frac{1}{|\mathcal{N}|} \sum_{\tau \in \mathcal{N}} \mathbf{x}_{ij+\tau}. \quad (6)$$

Here $\bar{\mathbf{x}}_{\eta^X_{ij}}$ is the mean of neighboring pixels' color vectors $\mathbf{x}_{\eta^X_{ij}} = \{\mathbf{x}_{ij+\tau}, \tau \in \mathcal{N}\}$, where $\mathcal{N}$ denotes the neighborhood of $(0,0)$ pixel. For example, $\mathcal{N} = \{(0,1),(0,-1),(1,0),(-1,0)\}$ for the first-order neighborhood, and if $\tau = (0,1)$, $\mathbf{x}_{ij+\tau} = \mathbf{x}_{i,j+1}$. $\mathbf{\Sigma}_X$ is the covariance matrix of $\mathbf{x}_{ij} - \bar{\mathbf{x}}_{\eta^X_{ij}}$.

Considering that $p(\mathbf{x}_{ij} \mid \mathbf{z}_{ij}, \mathbf{x}_{\eta^X_{ij}})$ in (3) is proportional to the product of two Gaussian pdfs for $p(\mathbf{z}_{ij} \mid \mathbf{x}_{ij})$ in (4) and $p(\mathbf{x}_{ij} \mid \mathbf{x}_{\eta^X_{ij}})$ in (5), the local MAP estimate $\hat{\mathbf{x}}_{ij}$ is explicitly derived as

$$\hat{\mathbf{x}}_{ij} = (\mathbf{\Sigma}_E^{-1} + \mathbf{\Sigma}_X^{-1})^{-1}(\mathbf{\Sigma}_E^{-1}\mathbf{z}_{ij} + \mathbf{\Sigma}_X^{-1}\bar{\mathbf{x}}_{\eta^X_{ij}}). \quad (7)$$

In order to solve (7) for all (i, j) pixels, their neighboring color vectors $\mathbf{x}_{\eta^X_{ij}}$ should be given. Since such a problem as shown in (7) can be solved iteratively, we rewrite Eq. (7) as

$$\mathbf{x}_{ij}^{(p+1)} = (\mathbf{\Sigma}_E^{-1} + \mathbf{\Sigma}_X^{-1})^{-1}(\mathbf{\Sigma}_E^{-1}\mathbf{z}_{ij} + \mathbf{\Sigma}_X^{-1}\bar{\mathbf{x}}^{(p)}_{\eta^X_{ij}}), \quad (8)$$

where p represents the pth iteration. Color components derived from a given JPEG compressed color image are used as initial values $\mathbf{x}_{ij}^{(0)}$s in this iterative estimation. If chrominance components are downsampled, interpolated chrominance components are used as their initial values. Implementation details of this image restoration method are given in [4].

5. Experimental Results

Experiments were carried out using four standard color images (Lena, Mandrill, Milkdrop, Peppers). These images are 512×512 pixels in size and 24 bit per pixel (bpp) full color images. The quantization tables for JPEG compression used in the following experiments are the standard ones published by the Independent JPEG Group [9]. Embedding CbCr components to DCT coefficients of Y component is carried out in the predetermined order, i.e., from the lowest frequency DCT coefficient to the highest frequency one in the zigzag scan order for each of which from the top left DCT block to the bottom right one in the raster scan order. Therefore, given the data size of CbCr components, they can be easily extracted from DCT coefficients of Y component. Here, the data size of CbCr components is embedded first before embedding CbCr components. Regarding $\mathbf{\Sigma}_E$ and $\mathbf{\Sigma}_X$ in (8), the two covariance matrices for each image can be estimated using each original image and its JPEG compressed one [4]. They are estimated in advance and their values are put in the header of JPEG file†.

First we show basic embedding performance of how much embedding reduces file size of JPEG color image and at the same time increases image degradation. In Table 1, embedding performance for Lena image as an example is shown for several quality factors which control image quality of JPEG images. Regarding data size, that of usual JPEG compressed color image, that of CbCr components in the JPEG color image, and that of JPEG gray image with CbCr components embedded are given in the table. Comparing these data sizes, it is found that the data size of JPEG color image is reduced by embedding but the amount of reduction is less than the amount of embedded CbCr components because the data size of Y component is increased by embedding. Regarding PSNR value, two kinds of PSNR values are given: one written as "PSNR-Color" is PSNR value of color image and the other written as "PSNR-Y" is that of only Y component image. Those PSNR values are given for a usual JPEG color image and a recovered color image from JPEG gray image with CbCr components embedded. The changes of quantized DCT coefficients of Y component by embedding cause image degradation of Y component image and then cause image degradation of color image.

Image qualities of the following four kinds of images in PSNR were calculated to evaluate performance of the proposed method.

- **(a)** Usual JPEG color image
- **(b)** Recovered color image from JPEG gray image with chrominance components embedded
- **(c)** Color image derived by applying the MAP based image restoration method to (a)
- **(d)** Color image derived by applying the MAP based image restoration method to (b)

Quality factor (qf) of JPEG image was changed from 50 to 90 with interval of 5.

Experimental results are shown in Fig. 2, where horizontal and vertical axes depict bpp value and PSNR value, respectively and four lines are results for the four kinds of images from (a) to (d). The leftmost and the rightmost points of each line correspond to qf=50 and qf=90, respectively. A portion of each line which is above the line (a) means that compression efficiency is improved in that portion, i.e., a larger PSNR value is achieved at the same bpp value and equivalently a less bpp is achieved at the same PSNR. Comparing (b) lines with (a) lines for the four images, more portions of (b) lines are slightly above (a) lines except for Pepper image. Comparing (c) lines with (a) lines, (c) lines are

†According to [4], one byte integer representation is enough for each element of the matrices. Considering that these matrices are 3×3 and symmetric ones, the overhead for sending the information on the two matrices is only 12 bytes.

Table 1 Embedding performance for Lena image.

	data size (bytes)			PSNR-Color(dB)		PSNR-Y(dB)	
quality factor	JPEG	CbCr	Embed.	JPEG	Embed.	JPEG	Embed.
50	24,268	3,088	22,099	32.065	31.547	35.825	34.829
60	27,930	3,594	25,274	32.492	31.995	36.470	35.557
70	33,805	4,389	30,371	33.039	32.586	37.336	36.590
80	43,823	5,876	39,168	33.770	33.344	38.546	37.885
90	68,661	9,606	60,311	34.896	34.506	40.820	40.030

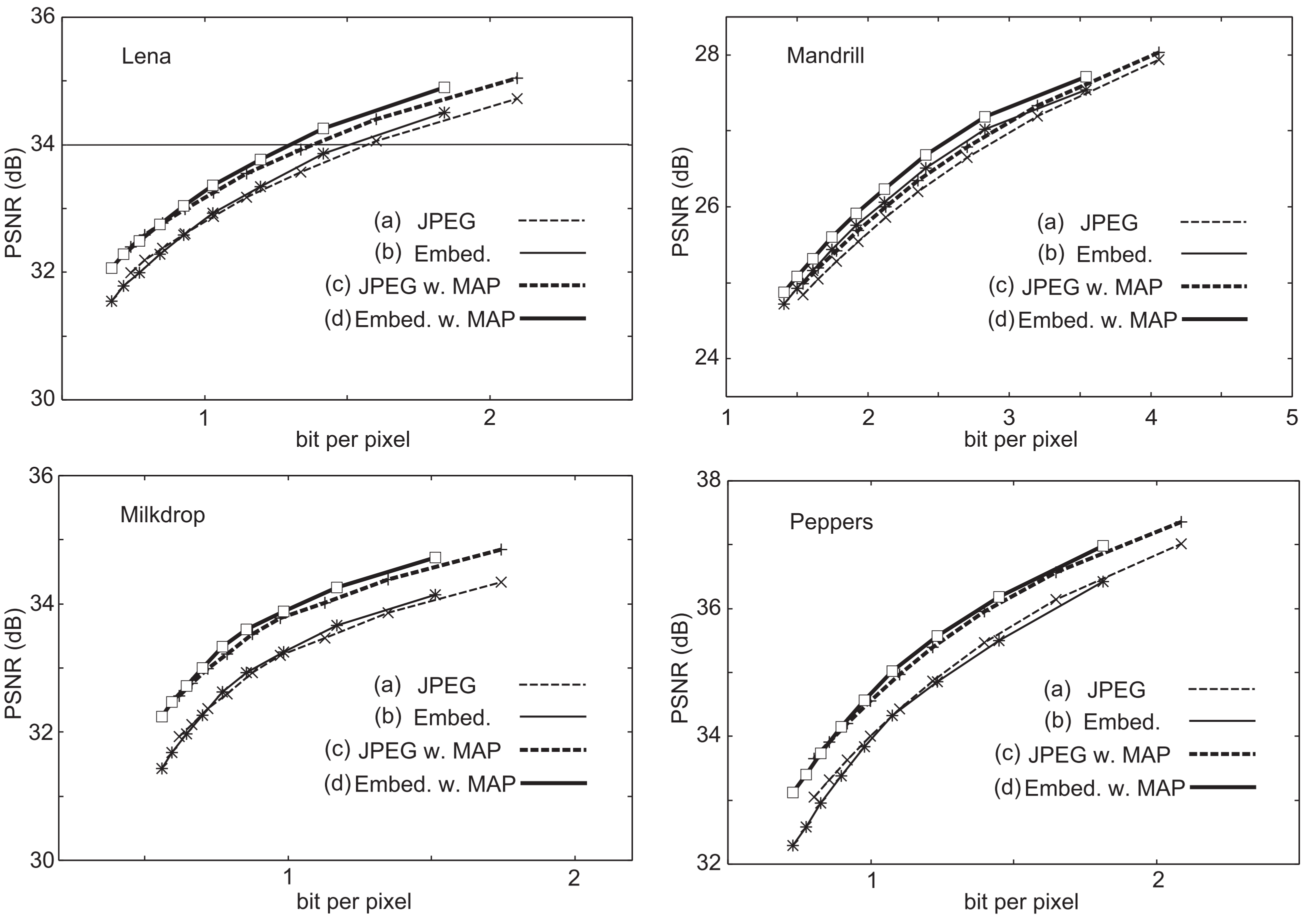

Fig. 2 Experimental results for four images.

far above (a) lines except for Mandrill image. It shows that image restoration improves compression efficiency significantly and its effect is generally (except for Mandrill image) much larger than that of embedding. Comparing (d) lines with (c) lines, (d) lines are generally above (c) lines. It shows that the use of both embedding and image restoration is most effective to improve compression efficiency.

Finally we describe how much bpp reduction is achieved by the proposed method. For Lena image as an example, by measuring on the horizontal line corresponding to PSNR=34 dB in Fig. 2, it is found that roughly 0.07, 0.19, and 0.27 bpp reductions are achieved by embedding only, by restoration only, and by both embedding and restoration.

6. Conclusions

As a new application of information hiding, this paper investigated its application to image compression. Aiming at improving compression efficiency of JPEG color images, we proposed an approach where the entropy-coded chrominance components are embedded into the quantized DCT coefficients of the luminance component. An image restoration method based on the MAP estimation was also applied to recover the image degradation caused by compression and embedding. Experimental results show that information hiding improves compression efficiency slightly and image restoration improves it more than information hiding does. It is found that the use of both information hiding and image restoration is most effective to improve compression efficiency. Though contribution of information hiding to improving JPEG compression efficiency is very small at present, we believe that it has a potential to improve compression efficiency even more if a better embedding method is developed.

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References

[1] I.J. Cox, M.L. Miller, J.A. Bloom, J. Fridrich, and T. Kalker, Digital Watermarking and Steganography, Morgan Kaufmann Publishers, 2008.
[2] B. Chen and G.W. Wornell, "Quantization index modulation: A class of provably good methods for digital watermarking and information embedding," IEEE Trans. Inf. Theory, vol.47, no.4, pp.1423–1443, 2001.
[3] H. Noda, M. Niimi, and E. Kawaguchi, "Application of QIM with dead zone for histogram preserving JPEG steganography," Proc. ICIP, vol.II, pp.1082–1085, 2005.
[4] H. Noda and M. Niimi, "Local MAP estimation for quality improvement of compressed color images," Pattern Recognit., vol.44, no.4, pp.788–793, 2011.
[5] M. Fujimura, S. Miyata, K. Hamano, H. Kuroda, and H. Imamura, "High efficiency coding of JPEG methods using watermarking technique," IEICE Trans. Inf. & Syst. (Japanese Edition), vol.J92-D, no.9, pp.1672–1676, Sept. 2009.
[6] D. Upham, http://ftp.funet.fi/pub/crypt/cypherpunks/steganography/jsteg/, 1997.
[7] A. Westfeld, "F5 - A steganographic algorithm: High capacity despite better steganalysis," Lect. Notes Comput. Sci., vol.2137, pp.289–302, 2001.
[8] H. Noda, "Information hiding using side information," IEICE Technical Report, EMM2011-1, 2011 (in Japanese).
[9] Independent JPEG Group, http://www.ijg.org/, 1998.